Performance of Ge-doped Optical Fiber as a Thermoluminescent Dosimeter

Mourad Benabdesselam, Franck Mady, Sylvain Girard, Yasmine Mebrouk, Jean Bernard Duchez, M. Gaillardin, Philippe Paillet

Performance of Ge-doped Optical Fiber as a Thermoluminescent Dosimeter

M. Benabdesselam[1], F. Mady[1], S. Girard[2], Y. Mebrouk[1], J.B Duchez[1], M. Gaillardin[3], P. Paillet[3]

1. Université de Nice Sophia Antipolis, LPMC UMR-CNRS 7336, Parc Valrose, 06108 Nice Cedex 2, France

2. Laboratoire Hubert Curien, UMR-CNRS 5516, 42000 Saint-Etienne, France

3. CEA, DAM, DIF, F-91297, Arpajon, France

Abstract (35 words) – The TSL response of Germanium doped optical fiber shows a good neutron- and proton- detection efficiency and high gamma ray sensitivity. This opens the way to a universal dosimeter, particularly interesting at therapy levels.

Corresponding and Presenting author:

Mourad BenabdesselamUniversité de Nice-Sophia Antipolis, LPMC UMR-CNRS 7336,
Parc Valrose, 06108 Nice Cedex 2, France
Phone: +33 4 92 07 63 32; Fax: +33 4 92 07 67 54
ben@unice.fr

Co-authors:

Franck Mady	Université de Nice Sophia Antipolis; Franck.MADY@unice.fr
Sylvain Girard	Université de Saint-Etienne; sylvain.girard@univ-st-etienne.fr
Yasmine Mebrouk	Université Nice Sophia Antipolis; Yasmine.mebrouk@unice.fr
Jean Bernard Duchez	Université de Nice-Sophia Antipolis; jbduchez@unice.fr
Marc Gaillardin	CEA, DAM, DIF; marc.gaillardin@cea.fr
Philippe Paillet	CEA, DAM, DIF; philippe.paillet@cea.fr

Session Preference: Dosimetry

Presentation Preference: Oral

I. INTRODUCTION

Radiation effects on both doped and undoped optical fibers have been investigated for a long time [1,4]. During the last decade, investigations on the potential of commercially available silica based optical fibers for ionizing radiation dosimetry have been carried out by the use of thermally stimulated luminescence (TSL) technique [5,6,7]. In these investigations, the authors were interested only by the TSL response sensitivity of the fibers towards photons and electrons irradiations and up to 10 krad absorbed doses.

The aim of this work is to demonstrate the actual ability of a Ge-doped optical fiber as TSL-mode dosimeter and to confirm its applicability. For this purpose, it seemed interesting to explore TSL response of such a dosimeter within a higher dose range of photons (X, γ) than 10 krad, at different dose rates and as well as its behavior towards neutrons and protons particles of different fluences.

After that, it became necessary to check if the Ge-doped optical fiber based dosimeter fits all the criteria required by dosimetry application (sensitivity, linearity, reproducibility, storage stability and reliability, etc) by comparison with the widely used commercial dosimeters (TLD).

In addition, it is well known that TSL dosimetry principle is based on the use of the property of TSL response relative to deep traps stable at room temperature (RT), which the population increases with the radiation-absorbed dose. In this technique, the deep level acts as “a memory cell” of the ionizing radiation dose. The trapping features (trap depth, frequency factor) of the involved point defect and its concentration in the TSL mechanism are among the critical parameters that control the response of the TSL dosimeter (TLD).

Moreover, unlike commercial fibers, this study focuses on samples produced on demand with the full knowledge of their physicochemical features as well as their synthesis and drawing conditions. This aims to further improve the performance of this promising dosimeter.

II. EXPERIMENTAL DETAILS

A. Studied Fibers

Multimode fibers (core and cladding diameters of 62,5 and 125 μm respectively) used in this work and named GeD1, GeD2 and GeD3 are from the same preform. The set is produced by Modified Chemical Vapor Deposition (MCVD) by iXFiber SAS. The difference between these three samples is due only to the drawing conditions. GeD1 was drawn with a speed of 70 m/min, GeD2 at 40 m/min and GeD3 at 22 m/min. Germanium content and doping profile of these fibers have already been reported by Alessi et al. [8, 9].

For TSL comparison, two commercially available TLDs (TLD700 and TLD500) were used. They are crystals of LiF: Mg, Ti and Al_2O_3: C respectively.

Due to heating, the polymer coating (250 μm diameter) is removed over a length of 2 to 3 m of fiber. Bare fiber obtained is cleaned, cut in small pieces of few millimeters in length and then put on an aluminum cupel for TSL analysis.

B. Irradiation Facilities

All irradiations have been performed at room temperature (RT). X irradiations were achieved by means of an X-ray tube (Cu target, 45 kV) at LPMC while a ^{60}Co gamma cell delivered γ rays with different dose rates at GAMRAY facility of TRAD in Toulouse, France. Two neutron particles energies have been used (0,8 and 14 MeV) thanks to PROSPERO and SAMES facilities at CEA Valduc, France. Irradiations by proton particles have been performed at TRIUMF, Vancouver, Canada.

C. TSL Setup

The TSL signal was recorded by means of a photomultiplier tube (PMT) between 250 and 600 nm from RT to 875 K with a linear heating rate of 2 K/s.

Emission spectra of TSL were detected by an optical multichannel analyzer (OMA) consisting of an optical fiber connected to a spectrograph equipped with a CCD array (Princeton Instruments) and whose spectral response is from 200 to 1100 nm.

III. RESULTS

A typical TSL curve for any irradiated fiber is shown in Fig. 1. It is composed of a dominant peak conveniently located at 560K, extremely sensitive and, thus, well suited for use in dosimetry. This relatively high peak position can be used to measure absorbed dose at room- and high temperature and in difficult-to-access areas, such as the "hermetic" zone in nuclear power plants. The trapping parameters relative to this peak have already been determined elsewhere [10]. The inset shows a blue-violet band centered at 400 nm, corresponding to the spectral distribution of this TSL peak. This emission appearing in the middle of the spectral response of all PM tubes can easily be extracted from the blackbody radiation of the heater, and is thus very useful for dosimetry work. This emission is well known and has already been attributed to the recombination of released electrons on the two-fold Ge centers (=Ge:) [11].

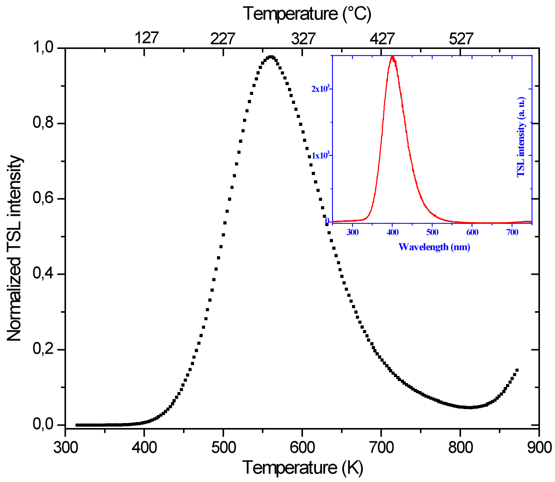

Fig. 1. TSL glow curve of a Ge doped fiber after γ-ray irradiation at RT.

In light of these findings, we decide to investigate first the TSL response of GeD fibers towards various radiations (γ, n, p) and then compare some basic but required dosimetric criteria of one of these fibers with two commonly used TLDs. For reasons of availability of beam time, this comparison is made only under X-rays, which are still available in the laboratory.

A. TSL responses to γ, n and p irradiations

The TSL response as a function of the γ absorbed dose for a dose rate of 500 rad/h as illustrated in Fig. 2. It shows a linear behavior within a wide range of dose and this, whatever the fiber. One also can mention that there is no obvious effect of the dose rate. Indeed, measurements were also made at rates of 30 and 100 rad/h, the difference between TSL responses of the 3 fibers is not significant.

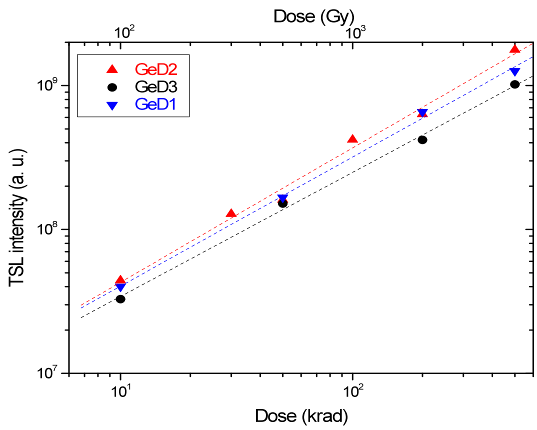

Fig. 2. TSL response as a function of the absorbed γ dose at 500 rad/h on the 3 fibers

Fig. 3 corresponds to the evolution of the TSL intensity as a function of the neutron fluence with energies of 14 and 0,8 MeV while Fig. 4 shows the variations of the response versus proton fluence on the fibers GeD1 and GeD2. These preliminary results (will be completed for the final paper) confirm that the fiber is sensitive to neutrons and protons and that TSL intensity is directly related to the fluence.

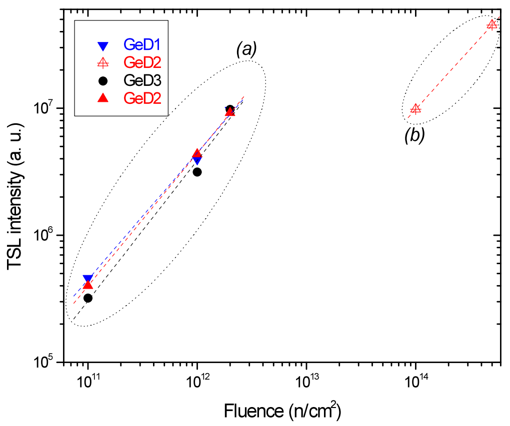

Fig. 3. TSL response as a function of neutron fluency of the fibers at 14 (a) and 0.8 MeV (b)

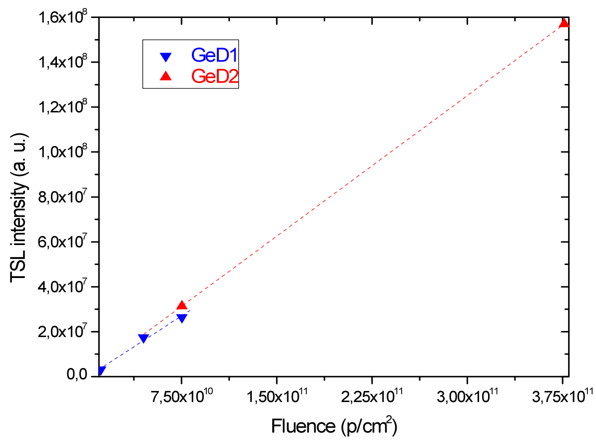

Fig. 4. TSL response as a function of proton fluence of GeD1 and GeD2 fibers

B. Comparison of dosimetric criteria

TSL sensitivity: Ge-doped fiber has a very high sensitivity of the TSL response and, as shown in Figs 2-4, for different types of radiations. From this observation, we conducted a comparative study of the TSL response under the same conditions of X-ray irradiation and readout with two TLDs. The aim of this comparison is to test the ability of the Ge-doped fiber for medical radiation dosimetry at therapy levels. This explains the choice of X-ray irradiation in this section, since it is the most prominent type of radiation, with electrons, used in radiotherapy.
Fig. 5 shows that under these same conditions, GeD2 fiber is at least more sensitive than TLD500.

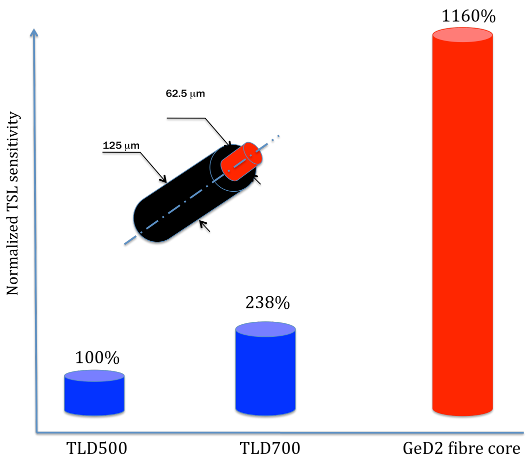

Fig. 5. Compared normalized TSL sensitivities of GeD2 fiber, TLD 500 and TLD700 under X-rays

TSL response to X-ray irradiation: Up to about 100 krad, the dosimetric peak TSL response of GeD2 fiber varies linearly with the absorbed dose without any significant dose rate dependence. This is particularly true at low dose levels (below 1 krad), which is useful in clinical dosimetry.

Repeatability: was estimated as less than 3% after 5 successive cycles. TLD700 chip is marketed with specification of 2% but after a heavy thermal treatment (1 h at 400 °C and 2h at 100 °C) before each use.

Fading: Thermal fading is of 5%, 8 hours post irradiation and the optical fading is 6% after 6 hours but reaches 30%, 90 hours post irradiation. This latter percentage might appear striking, but it is much less important than in the case of TLD500 for which the loss of information on the dose reaches 83% after only 10 min of light exposure [12].

Heating rate: in the case of TLD500, we observe a decrease in TSL efficiency by half when the heating rate increases by a factor 5. This physical effect known as thermal quenching of F centers in alumina [13] is completely absent in the fiber.

IV. DISCUSSION

Regarding the influence of the fiber elaboration parameters, which can be crucial for a possible large-scale use of the fiber as dosimeter, it is clearly shown here that regardless of the type of radiation, the TSL response is completely independent of the drawing parameters as the range covered in this work corresponds to the limits used by the fiber manufacturer for specialty optical fibers.
Fig 2 shows that the TSL response is substantially linear to total ionizing dose (TID) of γ-rays. This linearity of the response is appropriate in areas with high accumulation of dose.
Moreover, for a given photon (γ or X) dose, the intensity of the TSL signal remains constant as a function of dose rate. This absence of dose rate effect might be useful for external quality audits of treatment machines and intercomparison clinical studies in dosimetry.
The TSL response to neutron exposure (Fig. 3) presents a linear behavior similar to that seen in Fig. 2 for both energies of 14 (a) and 0,8 MeV (b).
Results show that the studied optical fibers have a good TSL response sensitivity to photons, neutrons and protons. Assuming that variations of this response as a function of dose and/or fluences, are approximately linear, as seen in Figs 2-4 and based on known models, one can easily draw (for the final paper) a new curve describing the TSL response versus the "ionizing" dose for all types of radiation (γ, n, p) and where one can observe a very good agreement between γ rays, neutron and proton particles.

All TSL responses presented here provide clear evidence of equivalences in rad between γ dose absorbed by the fiber on the one hand and the fluence of n and p particles and their energy on the other. The estimated equivalences are in good agreement with the results reported by Girard et al. [14]. In addition to these significant results, Ge doped fiber might be a potential candidate in the field of dosimetry at therapy levels, given its interesting properties: *(i)* TSL sensitivity is more than 10 times higher than one of the compared TLDs. *(ii)* Measurements are reproducible without any specification, unlike TLD700 that requires heavy regeneration protocol (1 h at 400 °C and 2h at 100 °C) before each use, causing a waste of time especially in routine dosimetry. *(iii)* The thermal fading is low and the optical one is by far better than that of TLD500 [10,12]. *(iv)* The thermal quenching is non-existent in the fiber.

V. CONCLUSION

The results show that Ge doped silica based optical fiber is very attractive in TSL dosimetry. In addition, the response independence of elaboration parameters will probably further reduces the already low cost of this material. Position of the dosimetric peak, storing the information on the absorbed dose, is so well located that it will also be capable to measure absorbed dose at high temperature and in difficult-to-access areas, such as nuclear power plants. The response shows a good neutron- and proton- detection efficiency and high gamma ray sensitivity.

At therapy levels Ge doped fiber meets all the main criteria required by the clinical dosimetry, often with, best features than the two compared TLDs on their own ground operation. It has good response linearity to gamma photons. It doesn't show any dose rate dependence and is potentially cheap.

In addition, fiber allows quantifying the influences of neutrons, protons, in the case of monoenergetic radiations but probably neutron spectra if we know their energy distribution.

This opens the way to a universal dosimeter, particularly interesting for therapy levels but also for the dosimetry associated with radiative tests like SEE measurements at low energy protons.

REFERENCES

[1] A. Alessi, S. Girard, M. Cannas, S. Agnello, A. Boukenter and Y. Ouerdane, Optics Express, 19 (2011), p. 11680

[2] A. Alessi, S. Agnello, S. Grandi, A. Parlato, F.M. Gelardi, Phys. Rev. B 80 (2009), p. 014103

[3] M. Fujimaki, T. Katoh, T. Kasahara and Y. Ohki, J. Phys. Condens. Matter 11 (1999), p. 2589

[4] E.J. Friebele, D.L. Griscom, and G.H. Sigel, J. Appl. Phys. 45 (1974), p. 3424

[5] A.A. Youssef, Y.M. Yamin, D.A. Bradley, Radiat. Phys. Chem., 61 (2001), p. 409

[6] S. Hashim, S. Al-Ahbabi, D.A. Bradley, M. Webb, C. Jeynes, A.T. Ramli, H. Wagiran, Applied Radiation and Isotopes, 67 (2009), p. 423

[7] A.T. Abdul Rahman, R.P. Hugtenberg, S.F. Abdul Sani, A.I.M. Alalawi, F. Issa, R. Thomas, M.A. Barry, A. Nisbet, D.A. Bradley, Applied Radiation and Isotopes, 70 (2012), p. 1436

[8] A. Alessi, S. Girard, C. Macandella, S. Agnello, M. Cannas, A. Boukenter, Y. Ouerdane, Journal of Non-Crystalline Solids 357 (2011), p. 1966.

[9] S. Girard, Y. Ouerdane, G. Origlio, C. Marcandella, A. Boukenter, N. Richard, J. Baggio, P. Paillet, M. Cannas, J. Bisutti, J.P. Meunier, R. Boscaino, IEEE Transactions on Nuclear Science, 55 (2008), p. 3473

[10] M. Benabdessselam, F. Mady, S. Girard, Journal of Non-Crystalline Solids 360 (2013), 9

[11] L. Skuja, "Optical Properties of Silica" in Defects in SiO_2 and Related Dielectrics: Science and Technology, p108 Edited by G. Pacchioni, L. Skuja and D.L. Griscom, 2000

[12] M. Moscovitch, R.A. Tawil, M. Svinkin, Radiat. Prot. Dosim. 47 (1993) 251

[13] S. McKeever, Thermoluminescence of Solids, Cambridge University Press (2005)

[14] S. Girard, J. Baggio, J. Bisutti, IEEE Transactions on Nuclear Science, VOL. 56, NO. 6, 2006